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The Chornobyl Accident: Estimation of Radiation Doses Received by the Baltic and Ukrainian Cleanup Workers

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During the first day after the explosion, the Chornobyl accident of April 26, 1986 exposed a few hundred emergency workers to high dose levels ranging up to 16 Gy, resulting in acute radiation syndrome. Subsequently, several hundred thousand cleanup workers were sent to the Chornobyl power plant to mitigate the consequences of the accident. Depending on the nature of the work to be carried out, the cleanup workers were sent for periods ranging from several minutes to several months. The average dose from external radiation exposure that was received by the cleanup workers was about 170 mGy in 1986 and decreased from year to year. The radiation exposure was mainly due to external irradiation from γ-ray-emitting radionuclides and was relatively homogeneous over all organs and tissues of the body. To assess the possible health consequences of external irradiation at relatively low dose rates, the U.S. National Cancer Institute is involved in two studies of Chornobyl cleanup workers: (1) a study of cancer incidence and thyroid disease among Estonian, Latvian and Lithuanian workers, and (2) a study of leukemia and other related blood diseases among Ukrainian workers. After an overview of the sources of exposure and of the radiation doses received by the cleanup workers, a description of the efforts made to estimate individual doses in the Baltic and Ukrainian studies is presented.

INTRODUCTION

The accident that took place on April 26, 1986 at the Chornobyl[2] nuclear power plant located in Ukraine, about 12 km south of the border with Belarus, occurred during a low-power engineering test of the Unit 4 reactor. Safety systems had been switched off, and improper, unstable operation of the reactor allowed an uncontrollable power surge to occur, resulting in successive steam explosions that completely destroyed the reactor and severely damaged the reactor building (*1*).

The workers involved in the accident in various ways can be divided into two groups: (1) the approximately 600 emergency workers who were involved in fire fighting and other emergency measures during the first day of the accident (April 26, 1986), and (2) the hundreds of thousands of cleanup workers, also called ''liquidators'' or ''recovery operation workers'', who were active in 1986–1990 at the power station or in the zone surrounding it for decontamination work, sarcophagus construction, other cleanup activities, and the operation of other units of the nuclear power plant.

Studies of cleanup workers provide an opportunity to add to current knowledge about the possible health consequences of exposure to relatively low doses of ionizing radiation received gradually over a period of several months. The Radiation Epidemiology Branch of the Division of Cancer Epidemiology and Genetics of the U.S. National Cancer Institute has been involved in two studies of Chornobyl cleanup workers: (1) a study of cancer incidence and thyroid disease among Baltic workers, and (2) a study of leukemia and other related blood diseases among Ukrainian workers. After a review of the sources of exposure and of the radiation doses received by the cleanup workers, a description of the Baltic and of the Ukrainian studies will be presented.

The designs of the studies that are discussed in detail in this article were approved by the appropriate Institutional Review Boards of the countries involved: the U.S., Ukraine and Estonia. All subjects who were screened in the two studies signed an informed consent form.

RADIATION DOSES RECEIVED BY THE EMERGENCY AND CLEANUP WORKERS

The following overview of the doses received by the workers is based on the 2000 report of the United Nations

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[2] Standard Ukrainian spellings of place names are used in this paper. The most noticeable differences are for the site of the accident and the nation's capital, Kyiv, but the names of other locations also differ from those used in previously published papers.

TABLE 1
Estimated γ-Ray Doses from External Irradiation Received by the Emergency Workers with Acute Radiation Sickness after the Accident (*2*)

Degree of acute radiation sickness	Dose interval (Gy)	Number of patients	Number of deaths	Number of survivors
Mild	0.8–2.1	41	0	41
Moderate	2.2–4.1	50	1	49
Severe	4.2–6.4	22	7	15
Very severe	6.5–16	21	20	1
Total	0.8–16	134	28	106

TABLE 2
Estimated Internal and External Doses to Victims of the Accident (*1*, *28*)

Number of patients	Internal thyroid dose until time of death (Gy)	External γ-ray dose (Gy)
6	0.02–0.09	4.3–8.2
7	0.1–0.49	2.9–11.1
7	0.5–0.99	5.5–10.2
3	1–4.1	3.5–5.6
Total: 23	0.02–4.1	2.9–11.1

Scientific Committee on the Effects of Atomic Radiation (*1*). More detailed information can be found in that report. The doses to emergency workers are presented, along with those to cleanup workers, to provide a more complete picture of the doses received by the workers involved in the accident.

Emergency Workers

The approximately 600 emergency workers include the staff of the plant, the firemen involved with the initial emergency, the guards, and the staff of the local medical facility. Most of them were at the reactor site at the time of the accident or arrived at the plant during the first few hours.

The workers that were most at risk were the firemen and the personnel at the power station on the night of the accident. The accident caused the deaths of 30 power plant employees and firemen within a few days or weeks (including 28 deaths due to radiation exposure). Some symptoms of acute radiation sickness were observed in 237 workers. After clinical tests, a diagnosis of acute radiation sickness was made in 134 of these persons.

The most important exposures were due to external irradiation (relatively uniform whole-body γ irradiation and β-particle irradiation of extensive body surfaces). The power plant personnel wore film badges that could not register doses in excess of 0.02 Gy. All of these badges were overexposed. The firemen had no dosimeters and no dosimetric control. Because all of the dosimeters worn by the workers were overexposed, they could not be used to estimate the γ-ray doses received through external irradiation. Information on the external doses received by the persons who were treated medically was obtained by means of biological dosimetry. The estimated external γ-ray doses for the 134 emergency workers with confirmed acute radiation sickness ranged from 0.8 to 16 Gy and are given in Table 1 (*2*). The skin doses from β-particle exposures evaluated for eight patients with acute radiation sickness ranged from 10 to 30 Gy (*3*).

Internal doses were determined from thyroid and whole-body measurements performed on the persons under treatment as well as from urine analysis and from post-mortem analysis of organs and tissues. For most of the patients, more than 20 radionuclides were detectable in the whole-body γ-ray measurements; however, apart from the radioiodines and radiocesiums, the contribution to the internal doses from the other radionuclides was negligible (*4*). Thyroid doses from internal irradiation, evaluated for 23 persons with confirmed acute radiation sickness, are shown in Table 2 and compared with the estimated γ-ray doses from external irradiation. The internal thyroid doses are, in general, much lower than the external γ-ray doses, and the two do not appear to be correlated.

Cleanup Workers

Workers from throughout the former Soviet Union were sent to the Chornobyl nuclear power plant to take part in mitigation activities, but most of them were from Belarus, the Russian Federation, and Ukraine. All together, about 600,000 persons (civilian and military) have received special certificates confirming their status as cleanup workers, according to laws promulgated in Belarus, the Russian Federation, and Ukraine. Of those, about 240,000 were military servicemen (*5*). The principal tasks carried out by the cleanup workers involved decontamination or construction. The reactor block, the reactor site, and roads leading to the reactor site were decontaminated, while the sarcophagus, a settlement for reactor personnel, the town of Slavutich, waste repositories, dams and water filtration systems were constructed (*6*). During the entire period, radiation monitoring and security operations were also carried out.

Of particular interest are the approximately 200,000 cleanup workers who were employed in the 30-km exclusion zone in 1986–1987, since the highest doses were received in this period. Most of these workers were 20–45 years old; about 95% of them were males. The remainder of the cleanup workers (about 400,000) includes those who worked inside the 30-km zone in 1988–1990 (a small number of workers are still involved) and those who decontaminated areas outside the 30-km zone from which residents had been evacuated. They generally received lower doses.

The most important pathway of exposure for the cleanup workers was external irradiation from the γ-ray emitters deposited on the surfaces of building materials or on the ground. This resulted in a relatively uniform irradiation of the whole body. The external γ-ray doses were, as much as possible, recorded by thermoluminescence dosimeters or

TABLE 3
Distribution of Doses to Cleanup Workers as Recorded in National Registries (*1, 29–31*)

Country and period	Number of cleanup workers	Percentage for whom dose is known	External dose (mGy)			
			Mean	Median	75th percentile	95th percentile
Belarus						
1986	68,000	8	60	53	93	138
1987	17,000	12	28	19	29	54
1988	4000	20	20	11	31	93
1989	2000	16	20	15	30	42
1986–1989	91,000	9	46	25	70	125
Russian Federation						
1986	69,000	51	169	194	220	250
1987	53,000	71	92	92	100	208
1988	20,500	83	34	26	45	94
1989	6000	73	32	30	48	52
1986–1989	148,000	63	107	92	180	240
Ukraine						
1986	98,000	41	185	190	237	326
1987	43,000	72	112	105	142	236
1988	18,000	79	47	33	50	134
1989	11,000	86	35	28	42	107
1986–1989	170,000	56	126	112	192	293

film badges and included in national registries. In addition to whole-body doses from external γ irradiation, cleanup workers received doses to the skin and to the lens of the eye from external β-particle irradiation as well as thyroid and whole-body doses from internal irradiation.

External Doses from Gamma Radiation

The national registry data for Belarus, Russia and Ukraine, presented in Table 3, show that the number of cleanup workers and the average recorded doses decreased from year to year, with a mean dose of about 140 mGy[3] in 1986 and of 100 mGy over 1986–1989. The decrease in recorded doses reflects the decrease in the dose limits, which, for most workers, were 250 mGy in 1986, 100 mGy in 1987, and 50 mGy in 1988 and in later years (*5, 7, 8*). The percentage of recovery operation workers with recorded dose follows the reverse tendency: It is low in 1986 and 1987, when the doses are relatively high, and it is higher in 1988–1989, when the doses are lower. Although the doses presented in Table 3 provide an indication of the exposures, they are not to be relied upon for epidemiological studies without further analysis because of the biases introduced by some of the methods of dose estimation and the falsification of data that may have occurred for a small percentage of workers.

Estimates of doses from external γ irradiation were generally obtained in one of four ways: (1) individual dosimetry for all civilian workers and a small proportion of the military personnel after June 1986 (in 1987, they were identified as those working in locations where the exposure rate was greater than 1 mR h^{-1}); (2) group dosimetry (an individual dosimeter was assigned to one member of a group of cleanup workers assigned to perform a particular task, and all members of the group were assumed to receive the same dose); (3) group assessment method (dose to the whole group of liquidators was assessed by a dosimetrist in advance with respect to the dose rate at work location and planned duration of work); or (4) time-and-motion studies (measurements of γ-radiation levels were made at various points of the reactor site, and an individual's dose was estimated as a function of the points where he or she worked and the time spent in these places). Methods (1), (2) and (4) were used for the civilian workers before June 1986; when the number of individual dosimeters was insufficient, methods (2) and (3) or their combination were used for the majority of the military personnel at all times (*6*).

Uncertainties associated with the different methods of dose estimation are assessed to be up to 50% for method (1) (if the dosimeter was correctly used), up to a factor of 3 for method (2), and up to a factor of 5 for methods (3) and (4) (*9, 10*).

External Doses from Beta-Particle Radiation

The dose to unprotected skin from β-particle exposures is estimated to have been several times greater than the γ-ray dose. Ratios of dose rates of total exposures (β particles + γ rays) to γ-ray exposures, measured at the level of the face, ranged from 2.5 to 11 for general decontamination work and from 7 to 50 for decontamination of the central hall of the Unit 3 reactor (*11*). It is worth noting that most of the skin was shielded by clothes and that the β-particle dose to protected skin was much smaller than the dose to unprotected skin.

The problem of β-particle dose assessment to the eye lens was addressed in the framework of the Ukrainian-American Chernobyl Ocular Study, which is a cohort study of cataract among 8,607 Ukrainian recovery operation workers (*12*). The assessment of the β-particle dose was derived from the γ-ray exposure of the subjects. Gamma-ray to β-particle dose conversion coefficients were calculated using Monte Carlo procedures for a variety of β-particle emitter spectra and of conditions of exposure. It was found that the distribution of individual β-particle/γ-ray dose ratios is quite broad, with a median value of 0.51 and a 95th percentile of 1.84 (*12*). The β-particle/γ-ray dose ratios for the eye lens are substantially lower than those for unprotected skin because of the rapid attenuation of the β

[3] Exposures to external radiation for the Chornobyl cleanup workers are reported in the literature in Roentgens (R), grays (Gy), or sieverts (Sv). For the sake of consistency, the exposure to external radiation, which is relatively uniform over all organs and tissues of the body, is expressed in grays in this paper. Because most of the radiation exposure was from γ rays of moderate energy, it is assumed that 1 Gy = 1 Sv = 100 R.

particles in tissue. In addition, the Monte Carlo procedures used in the Ukrainian-American Chernobyl Ocular Study (*12*) are expected to yield more realistic results than those used by Osanov *et al.* (*11*).

Internal Doses

Because of the abundance of ^{131}I and of shorter-lived radioiodines in the environment of the reactor during the accident, the cleanup workers who were on the site during the first few weeks after the accident may have received substantial thyroid doses from internal irradiation. Information on the thyroid doses is very limited and imprecise. On the basis of *in vivo* thyroid measurements carried out on more than 600 cleanup workers from April 30 through May 7, 1986, it was estimated that the dose was less than 0.15 Gy for 64% of the workers, between 0.15 and 0.75 Gy for 32.9% of the workers, and between 0.75 and 3 Gy for the remaining 3% of the workers (*13*).

Internal doses resulting from intakes of radionuclides other than the radioiodines (such as ^{90}Sr, ^{137}Cs and ^{239}Pu) have been assessed for about 300 cleanup workers who were at the reactor site at the time of the explosion or very soon afterward (*10*, *14*, *15*). The dose assessment for these workers, who were monitored from June to September 1986, was based on the analysis of whole-body measurements and of radionuclide concentrations in excreta. The average value of the effective dose committed by the radionuclide intakes was estimated on the basis of ICRP Publication 30 (*16*) to be 85 mSv. In comparison, there are reasons to believe that the effective doses that these workers received from external irradiation, although not reported, were greater than 250 mSv, since the workers showed clinical signs caused by radiation exposure.

DESCRIPTION OF AND DOSIMETRY FINDINGS FROM THE BALTIC STUDY

The Baltic study was started in 1992 with the aims of assessing the health effects of exposure to radiation among a cohort of cleanup workers from Estonia and validating the recorded radiation dose estimates by biodosimetric methods (*17*). Although it was later extended to Latvia and Lithuania, most of the results available are for the Estonian cohort.

Characteristics of the Cohort

Nearly 2% of the male population of Estonia aged 20–39 years was sent to Chornobyl to assist in the cleanup activities after the reactor accident (*17*). A cohort of 4,833 men from Estonia who worked in the Chornobyl area was assembled in 1992. Since information on persons sent to Chornobyl was held by various governmental and non-governmental bodies, four independent sources of information were used: (1) records of the former Soviet Army, which were in the possession of the General Staff of Estonian Defense Forces; (2) the Estonian Chornobyl Radiation Registry, which was set up in 1991 as a subdivision of a registry for all states of the former USSR; (3) the Estonian Chornobyl Committee, established in 1989 as a result of expanding grassroots activity promoting the interest of cleanup workers; and (4) the Ministry of Social Welfare.

TABLE 4
Types of Work in Chornobyl Area Performed by Cleanup Workers from Estonia, and Mean Dose for Workers Performing Each Task (*18*)

Type of work	Percentage of workers[a]	Mean dose (mGy)
Construction of sarcophagus	1.1	150
Cleaning debris from roof	14.3	146
Removal of topsoil	54.5	116
Forest decontamination	15.4	120
Other decontamination work	18.5	123
Transport	44.0	107
Building demolition	21.0	101
Construction	25.0	112
Radiation measurement	5.1	104
Guard duty	1.7	98

[a] Percentages total more than 100% due to individual workers performing more than one type of work.

Information obtained from 3,704 persons from a detailed questionnaire indicated that approximately 85% of the cleanup workers were military reservists who had been sent to Chornobyl as part of military training exercises, while the remaining 15% consisted of individuals who were fulfilling their regular military duty, were contract workers (mostly builders), or were sent to Chornobyl for other reasons. About 63% of the workers were sent to Chornobyl in 1986, 23% in 1987, 12% in 1988, and 2% later.

The amount of time spent in the Chornobyl area ranged from 1 to 834 days, with a median value of 94 days. Thirty-six percent of the workers reported having worked within the immediate vicinity of the accident site; 11.5% worked on the roofs near the damaged reactor, clearing the highly radioactive debris. The most commonly performed task was the removal and burial of topsoil (55% of the workers).

Estimates of Dose from External Irradiation

Information on doses from external irradiation was abstracted from all sources, but primarily from military lists and the questionnaires. About 84% of the cohort had a recorded dose. The questionnaire data indicate that about half of the workers did not wear a dosimeter; for these workers, the recorded dose was probably obtained by inference. The recorded dose ranged from 0.2 to 605 mGy, with a mean value of 109 mGy (*17*). The mean recorded doses were higher for the 1986–1987 workers (120 mGy in 1986 and 98 mGy in 1987) than for the 1988–1989 workers (37 mGy).

With respect to the type of work performed (Table 4), the mean recorded dose was highest for the relatively small group of men who worked on the sarcophagus and for those who worked clearing debris from roofs of nearby buildings. However, the differences in mean dose among the different tasks were small (*18*).

Estimates of Dose from Internal Irradiation

Doses from internal irradiation were rarely quantified. With respect to thyroid doses, the likelihood of exposure to radioiodines was assessed indirectly through consideration of date of service and use of stable potassium iodide, which was asked about in the questionnaire (*18*). Administration of stable iodine was reported by approximately 18% of the respondents (*17*).

Biological Dosimetry

The study design also incorporated biological indicators of exposure based on the glycophorin A (GPA) mutational assay of red blood cells and chromosome translocation analyses of lymphocytes (FISH). Biodosimetry was not used to estimate doses to individual cleanup workers but rather to group workers in presumptive ordinal categories of exposure. Assays were carried out blinded with respect to recorded dose.

GPA assays were conducted in blood samples from 453 Estonian and 281 Latvian cleanup workers and from 27 Estonian and 24 Latvian unexposed reference subjects. A set of 94 group-matched historical U.S. unexposed reference subjects was also used (*19*). It was found that the GPA results observed for the exposed populations were not substantially elevated over control values. However, given the sensitivity of the GPA assay, it is unlikely that a biological effect could have been detected with that technique in a population that received a protracted mean dose of the order of 100 mGy (*19*).

A FISH analysis of lymphocyte cultures from 118 Estonian workers (103 mGy mean recorded dose; 250 mGy maximum), 29 Estonian controls, and 21 American controls was conducted in three laboratories (*20*). The investigators were unable to detect any increase in the mean, median and range in chromosome aberrations among the Estonian cleanup workers in comparison to the controls. Because they expected to find an increase in the mean frequency of chromosome translocations of more than 40–65% in a population that received a mean exposure of about 100 mGy, they concluded that it is likely that recorded doses for these cleanup workers overestimated their average bone marrow doses, perhaps substantially (*20*).

DESCRIPTION OF AND DOSIMETRY FINDINGS FROM THE UKRAINIAN STUDY

In 1988, President Reagan of the U.S. and General Secretary Gorbachev of the Communist Party of the USSR signed a Memorandum of Cooperation promoting cooperation between the two countries in the fields of civilian nuclear reactor safety and health effects of nuclear reactor operations and accidents. Within the framework of that Memorandum, the U.S. National Cancer Institute (NCI) was asked to develop and implement a long-term epidemiological study of leukemia among the Chornobyl cleanup workers. It was determined that the best location for such a study would be in Ukraine, principally because this republic contained the largest number of cleanup workers among republics of the USSR and the Research Center for Radiation Medicine (RCRM) in Kyiv had excellent personnel and resources for such an investigation. A bi-national agreement for implementation of the proposed study of leukemia and some leukemia-related disorders was signed in October of 1996 by officials of the two countries. In the first phase of the investigation, from 1996 to 1999, various pilot studies were performed to establish that the planned study was feasible. The study itself was undertaken in 1999 and is expected to be completed in 2005.

The cohort for the study includes all the men who worked in the 30-km zone around the power plant between 1986 and 1990, were resident in Kyiv City or in one of five oblasts of Ukraine (Cherkasy, Chernihiv, Dnipopetrovsk, Kharkhiv and Kyiv), and are listed in the Chornobyl State Registry (SRU) of Ukraine. About 110,000 Ukrainian cleanup workers satisfy those criteria. The epidemiological study is designed as a case-control study nested within the cohort of 110,000 workers. Cases include all workers who were diagnosed with leukemia or related blood diseases.[4] Controls are randomly selected members of the cohort who match the cases in age and time of cleanup work.

The case-control design also is being used in similar studies conducted by the International Agency for Research on Cancer (IARC) among the cleanup workers of Russia and Belarus. To harmonize the work carried out in Ukraine, Russia and Belarus to obtain reasonably reliable and comparable dose estimates for the Chornobyl cleanup workers, an International Dosimetry Group was set up in cooperation with IARC. Individual doses have been estimated for all subjects of the IARC and NCI studies. They are being verified and will not be made publicly available for some time. It is, however, deemed to be of interest to describe the methods that have been used to estimate the doses and the difficulties that have been encountered in the process.

Characteristics of the Cohort

About 95% of the approximately 110,000 Chornobyl cleanup workers in the cohort are males, and most were in the 26–35-year age range while working at Chornobyl. Information available for most of the cleanup workers includes name, sex, birth date, identification number, residence history, work dates for Chornobyl service, date of first registration in the database, and medical diagnoses. As shown in Table 5, the SRU contains official dose records (ODR) related to external irradiation for only about one-

[4] Lymphoma, multiple myeloma and myelodysplasia.

TABLE 5
Distribution of Officially Recorded Doses from External Irradiation among Cohort Members[a]

Dose (mGy)	Year of participation: 1986	1987	1988	1989	1990	Unknown or after 1990	Total
<50	1376	1066	4520	3531	955	8	11,456
50–149	2233	10,499	1716	355	40	10	14,645
150–249	7697	2121	41	14	1	24	9898
250–349	3722	202	10	4	0	1	3939
350–449	52	4	1	3	1	0	61
450–549	25	4	2	9	0	0	40
550–649	19	3	2	0	0	0	24
650–749	6	1	0	0	0	0	7
750–849	3	1	1	1	0	0	6
850–949	2	2	0	0	0	0	4
950–1050	3	2	2	0	0	0	7
>1050	53	3	9	3	0	1	69
Number with recorded doses	15,191	10,589	5967	3891	1044	52	36,734
Number without recorded doses	55,703	5885	2238	1127	440	8518	73,911
Total number	70,894	16,474	8205	5018	1484	8570	110,645

[a] Yu. Belayev and B. Ledoschuk, Research Center for Radiation Medicine, 254050 Kyiv, Ukraine, personal communication, 2003.

third of the cleanup workers. The percentage of cleanup workers with ODR varied from oblast to oblast, ranging from 1.4% in Kyiv oblast to 66% in Chernihiv oblast. The arithmetic mean dose recorded for all Ukrainian cleanup workers in the cohort during 1986–1990 is 132 mGy, while the geometric mean dose is 94 mGy.

A serious deficiency of the Registry is that it does not include any information regarding group affiliation at the Chornobyl site, the type of cleanup work performed, or the method used to estimate the recorded radiation dose. This information would have been useful to confirm the validity of the recorded dose levels, as well as to provide indications on the quality of the available dosimetric information. As was demonstrated by Ilyin *et al.* (*21*), different organizations involved in cleanup activities had different characteristics both in terms of dose management practices (and consequently dose levels) and methods of dosimetry (and consequently uncertainties associated with dose estimates). These issues were addressed in a limited postal survey related to cleanup workers from Dnipropetrovsk, Donetsk, Kharkiv, Poltava and Zaporizha Oblasts. A total of 13,820 questionnaires were sent to cleanup workers residing in those oblasts. In return, 4,634 completed questionnaires were received (34% response rate). The results of this survey show that 86% of the cleanup workers in the sampled oblasts belonged to the category of ''partisans'' (military reservists) and that the percentage of cleanup workers who were professional nuclear reactor workers, with presumably good-quality dosimetry, was very low (less than 3%). The most typical tasks performed by cleanup workers were decontamination (62% of respondents), driving vehicles (22%), removal of reactor debris from the roof (19%), and logistic support (17%). Many cleanup workers performed several tasks, so that the percentages given above do not add up to 100%. The most typical localizations of work were the ''industrial site'' (that is, within the fenced area surrounding the Chornobyl nuclear power plant) and the 10-km zone. The distribution of the time spent by the Ukrainian military cleanup workers within the 30-km zone is shown in Fig. 1. The values range from 1 to 365 days, with a mean of 71 days.

A general characteristic of the ''partisans'' is that they had no experience or interest in radioactive decontamination (and therefore have a poor recollection of the work that they performed) and that their doses were obtained through group monitoring. Group monitoring was accomplished in one of two ways: (1) An individual dosimeter was provided to only one member of a group of cleanup workers assigned to perform a particular task, and all members of the group were assumed to receive the same dose; or (2) a dosimetrist measured the dose rate at the location where the task was to be performed and determined the amount of time that would correspond to the dose allowed for the task that was considered. The military reservists would then carry out their work during the allotted time and would be assigned the allowed dose. The uncertainties associated with group monitoring have been assessed to be up to a factor of 3 (*9*). In addition, prior to the beginning of the study, concern had been expressed that many doses had been assigned administratively and did not represent the reality. This concern was based on the observation that many ODR doses are just below 250 mGy, which was the maximum admissible in 1986, and that few are greater than 250 mGy. However, an investigation of the recorded dose

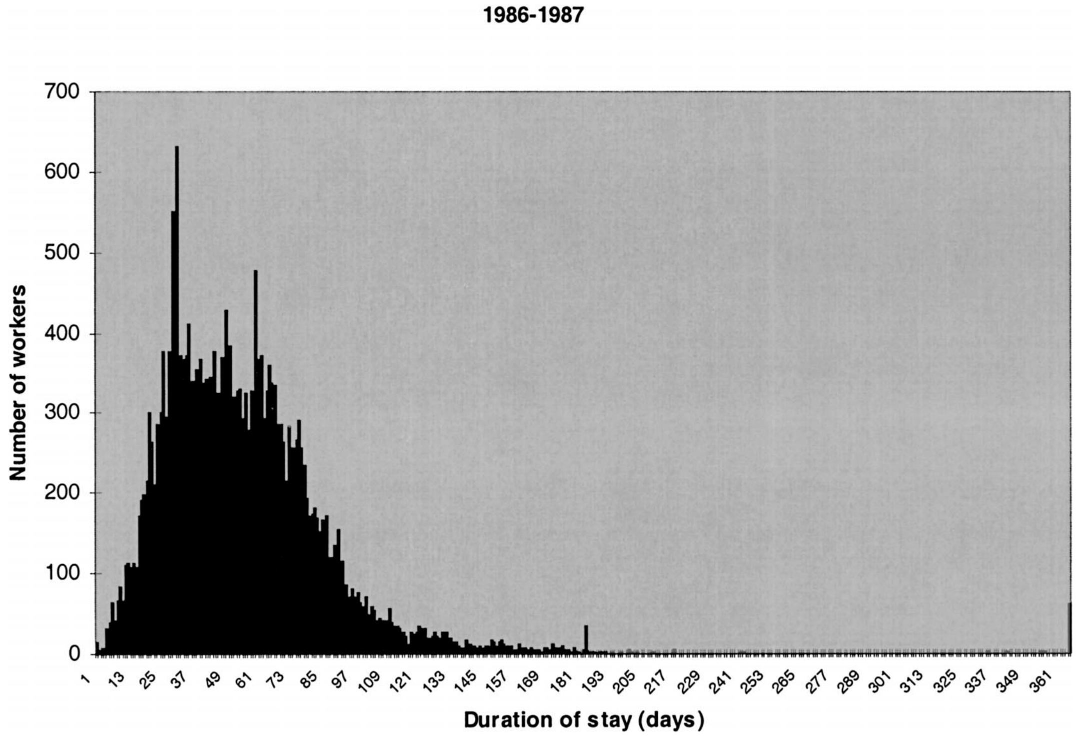

FIG. 1. Distribution of work duration in the 30-km zone for Ukrainian military liquidators in 1986–1987.

rates seems to indicate that, by and large, the ODR doses have not been falsified (*22*). This is not to say that all of the ODR doses have to be accepted as true doses. In a preliminary investigation of the high-dose records of the Chornobyl State Registry, it was found that there were obviously mistyped values and errors in the placement of the decimal point. In addition, in a comparison of a sample of SRU dose records with information from other sources thought to be reliable, complete agreement was found for only 40% of the sample, and deviations in excess of 10% occurred for 14% of the cleanup workers. Because of the incompleteness of the dose records in the Registry and of a lack of reliability in the dose records for individual cleanup workers, it was decided to seek an indirect method of estimation that could be applied to all members of the study. The information available in the SRU on the officially recorded doses will be used only for comparison purposes.

Estimates of Dose from External Irradiation for all Members of the Study

The main purpose of the dosimetric work was to investigate whether the doses for all cleanup workers involved in the study could be estimated reliably using the same method for all cases and controls.

There are two types of dosimetry sources that are available or can be obtained: (1) the archived information: databases, records, and documents that were prepared when the main cleanup activities were conducted (from 1986 to 1990); this information is dispersed in many locations in Ukraine and in Russia; and (2) the doses that can be reconstructed retrospectively, either by means of instrumental biological methods (EPR, FISH) or by expert estimation based on personal interviews combined with a general knowledge of the dose patterns or of the radiation fields (analytical dose reconstruction methods). Because the biological methods cannot be used for all subjects, due to lack of sensitivity (FISH) or of biological material (EPR), an analytical dose reconstruction method called RADRUE (Realistic Analytical Dose Reconstruction with Uncertainty Estimation) was developed by the International Dosimetry Group for the purposes of the IARC and Ukrainian-NCI studies. With this method, a dose estimate could be obtained for any cleanup worker, the uncertainty of which would depend on the availability and accuracy of the environmental measurements as well as on the degree to which the cleanup worker would remember his work history. An implication was that all cases or their proxies and all controls would be required to provide detailed work histories by interview. Such interviews have been conducted for all subjects or their proxies.

The RADRUE method is based on the compilation of the description of the work history of the cleanup worker and of the information on dose-rate fields in the locations where the cleanup worker spent time. The retrospective dose evaluation for each cleanup worker consists of three stages:

1. Personal interview with the cleanup worker in which he answered a detailed questionnaire regarding his affilia-

tion, work history and itinerary from work station to resting place.
2. An expert assessment of the answers provided during the interview. At that stage, the work history and itineraries are broken down into a set of separate episodes (clearly identified activities), which in turn are also broken down into frames during which exposure rates could be considered to be constant. Best estimates and uncertainties of the exposure rates for each episode and of the duration of each frame are assigned by the expert.
3. A computer code is run to estimate bone marrow doses, together with their uncertainties.

The tools required to perform the dose evaluation include:

1. A detailed questionnaire that can be used for any cleanup worker, irrespective of his affiliation, type of work, or duration of work at the Chornobyl site. In case the cleanup worker is dead or too incapacitated, the questionnaire is administered to two proxies: (a) a close relative who can respond to the questions of an administrative nature and identify co-workers of the subject, and (b) a co-worker to obtain information on the work history of the subject. The detailed questionnaire was tested on a number of cleanup workers and proxies and was administered to the cases and controls involved in the study.
2. A good knowledge of the radiation field at all locations of interest within the 30-km zone and at all times from the time of the accident in 1986 through 1990. For that purpose, all relevant information that was readily available was collected and processed.
3. Conversion coefficients from exposure rate to bone marrow dose rate for all radiation fields that were encountered. These conversion coefficients should also take into account the fact that some cleanup workers wore protective equipment, such as lead aprons. The determination of these conversion coefficients has been completed.

Biological Dosimetry

The dose estimates obtained by means of the RADRUE method need to be verified using independent and objective methods. For that purpose, two such methods have been developed and tested:

1. The electron paramagnetic resonance (EPR) method, which yields an estimate of the radiation dose received by the tooth examined until extraction. EPR dosimetry with teeth has a long record of different tests and cross-calibrations (*23, 24*). Among those tests, the most clear-cut judgment of the performance of the EPR dosimetry is provided by blind intercalibration when test teeth are exposed *in vitro* to precisely determined doses and then measured by EPR dosimetry laboratories that do not know the nominal dose values. Among intercalibrations of this type, the most notable are those organized by the International Atomic Energy Agency (IAEA) (*25–27*). The RCRM took part in both intercalibrations and proved its ability to reconstruct doses in excess of 100 mGy with average error of about 15%. Although EPR appears to have the best sensitivity and accuracy, when compared to other methods for estimating radiation doses of the cleanup workers, for all radiation doses down to about 50 to 100 mGy, it is recognized that the evaluation of the doses received *in vivo* faces difficulties due to the exposure to additional sources of radiation such as UV light (in particular, solar) and medical and dental X-ray doses. Special attention was paid to the prevention of the effect of these confounding factors: Only molars and premolars (which do not receive solar UV radiation) were used for the tests and the absence of X irradiation was assessed by checking that the two parts of the tooth—buccal and lingual—gave the same signal. So far, approximately 2,400 teeth from 1,800 workers have been found to be appropriate for EPR dosimetry, and about 300 doses have been reconstructed by means of the EPR technique.
2. The fluorescence *in situ* hybridization (FISH) method, which scores stable translocations in human blood lymphocytes and relates translocation frequency to dose, is a time-intensive and expensive method with a lower limit of detection of about 150 to 200 mGy (*20*). Encouraging results have been obtained in the comparison of the doses obtained by the FISH technique and of the doses recorded in the Registry that are greater than 250 mGy. However, the use of the FISH method is limited because many of the subjects are expected to have received doses near or substantially below the lower limit of detection and also because of the long time it takes to carry out an analysis.

The consistency of the dose estimates obtained by the two methods (RADRUE and EPR) for doses greater than 50 mGy and by the three methods (RADRUE, EPR and FISH) for doses greater than 250 mGy is being evaluated. A calibration exercise in which bone marrow doses are to be estimated for 100 workers of various affiliations is in progress. The results also will be compared with the dose estimates that are available in the State Chornobyl Registry and other Registries.

SUMMARY

1. Several hundred thousand cleanup workers were involved between 1986 through 1990 in the mitigation of the Chornobyl accident.
2. Most of the radiation exposure received by the cleanup workers was from external irradiation. The time they were exposed varied from a few minutes to a few months.

3. Doses from external irradiation averaged 170 mGy in 1986 and decreased from year to year.
4. The Radiation Epidemiology Branch of the Division of Cancer Epidemiology and Genetics of the U.S. National Cancer Institute has been involved in two studies of Chornobyl cleanup workers: (a) a study of cancer incidence and thyroid disease among Estonian, Latvian and Lithuanian workers; and (b) a study of leukemia and other blood diseases among Ukrainian workers.
5. One of the aims of the Baltic study, which was undertaken in 1992, was to validate the recorded radiation dose estimates by biodosimetric methods. It was found that the GPA and FISH results were not substantially elevated over control values.
6. The Ukrainian study was undertaken in 1996. Because recorded doses are not available for about two-thirds of the Ukrainian cleanup workers, an analytical method of dose reconstruction that could be applied to all workers was developed. Biodosimetry methods (EPR and FISH) also were applied to assess the validity of the results obtained with the physical method of dose reconstruction.

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